EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

Radioactivity - Radionuclides - Radiation
9th Nuclear Science Training Course with Nucleonica
(Karlsruhe, Germany, 25th-26th November 2007)

Friday, 26th November 2007

Interaction of photons with matter

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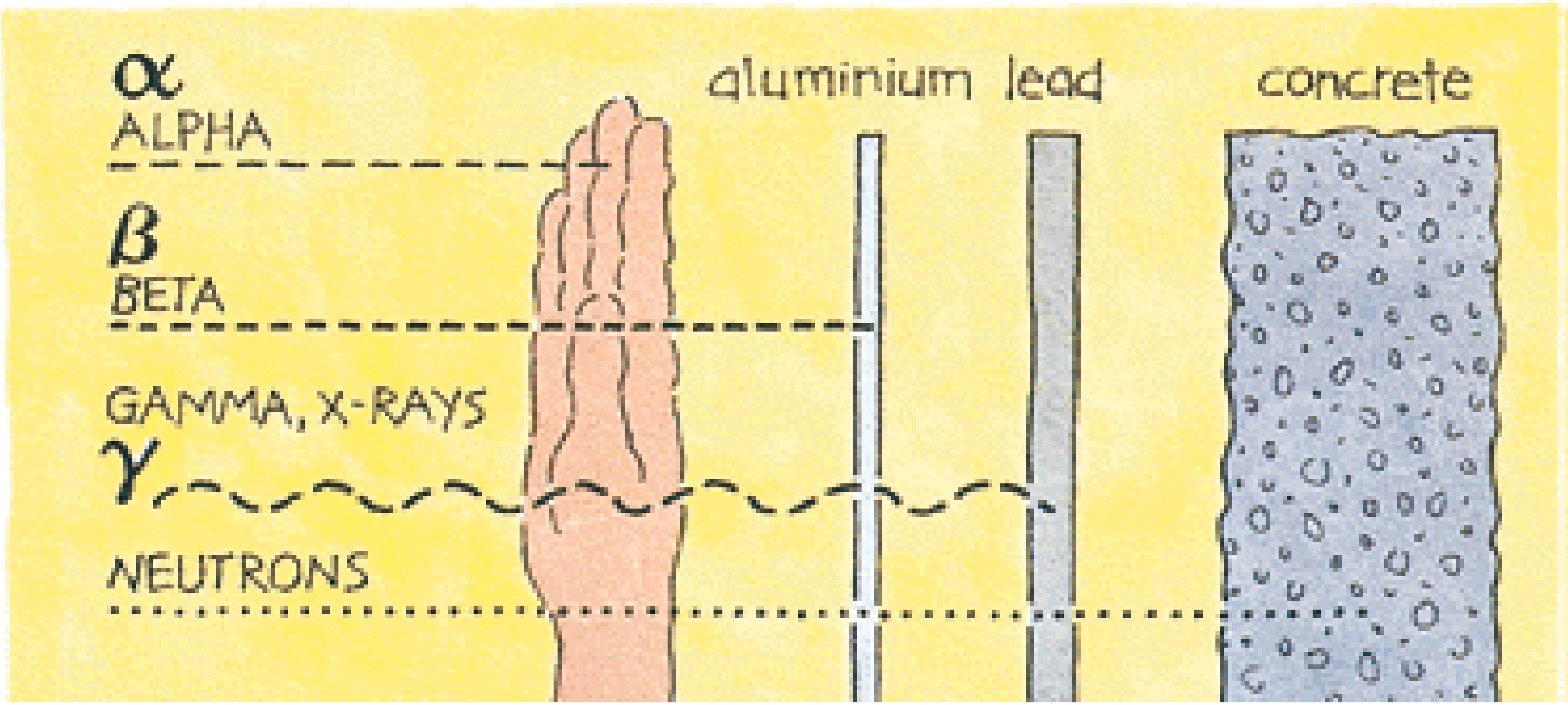
Interaction of photons

Classification of radiations

Type	Radiation	Penetrability
charged particles	• heavy (alpha) • light (beta)	range ~10^{-5} m range ~10^{-3} m
uncharged radiation	• EM (gamma, X) • neutrons	$d_{1/2}$ ~0.1 m $d_{1/2}$ ~0.1 m



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The photon

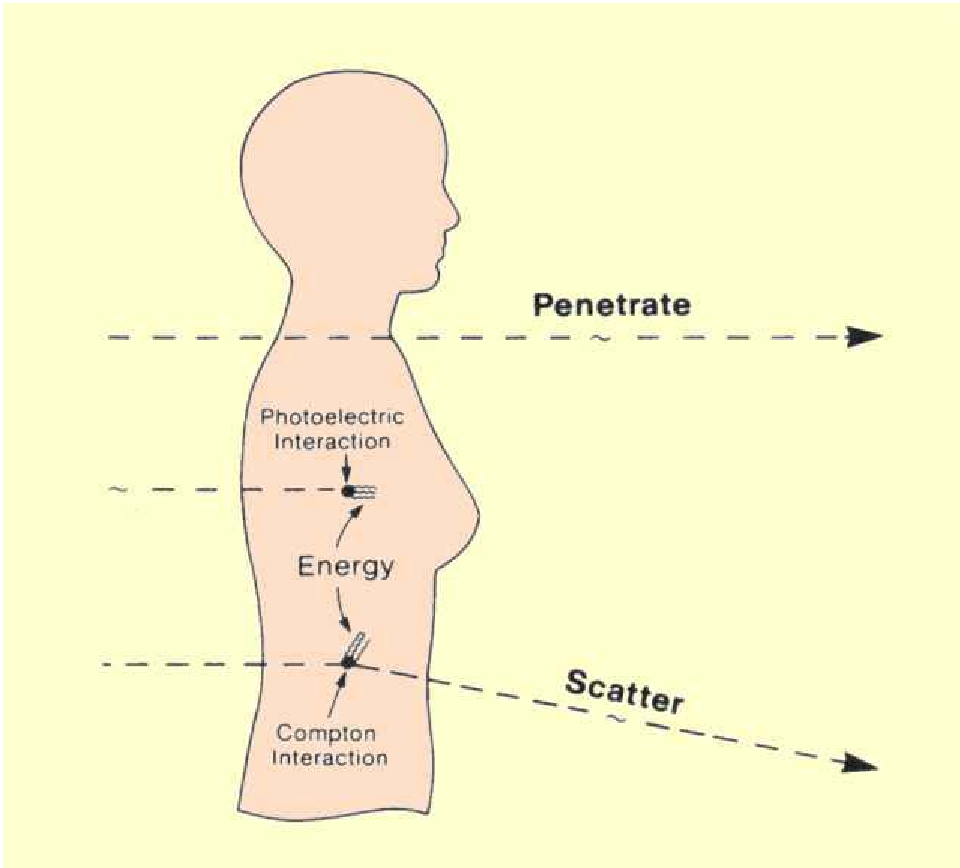
- ✓ Photons are "particle-like" manifestation of electromagnetic waves.
- ✓ Photon energy is proportional to frequency with a proportionality (Plank's) constant, h = 4.14 x 10^{-21} MeV-sec

$$E = h\nu$$

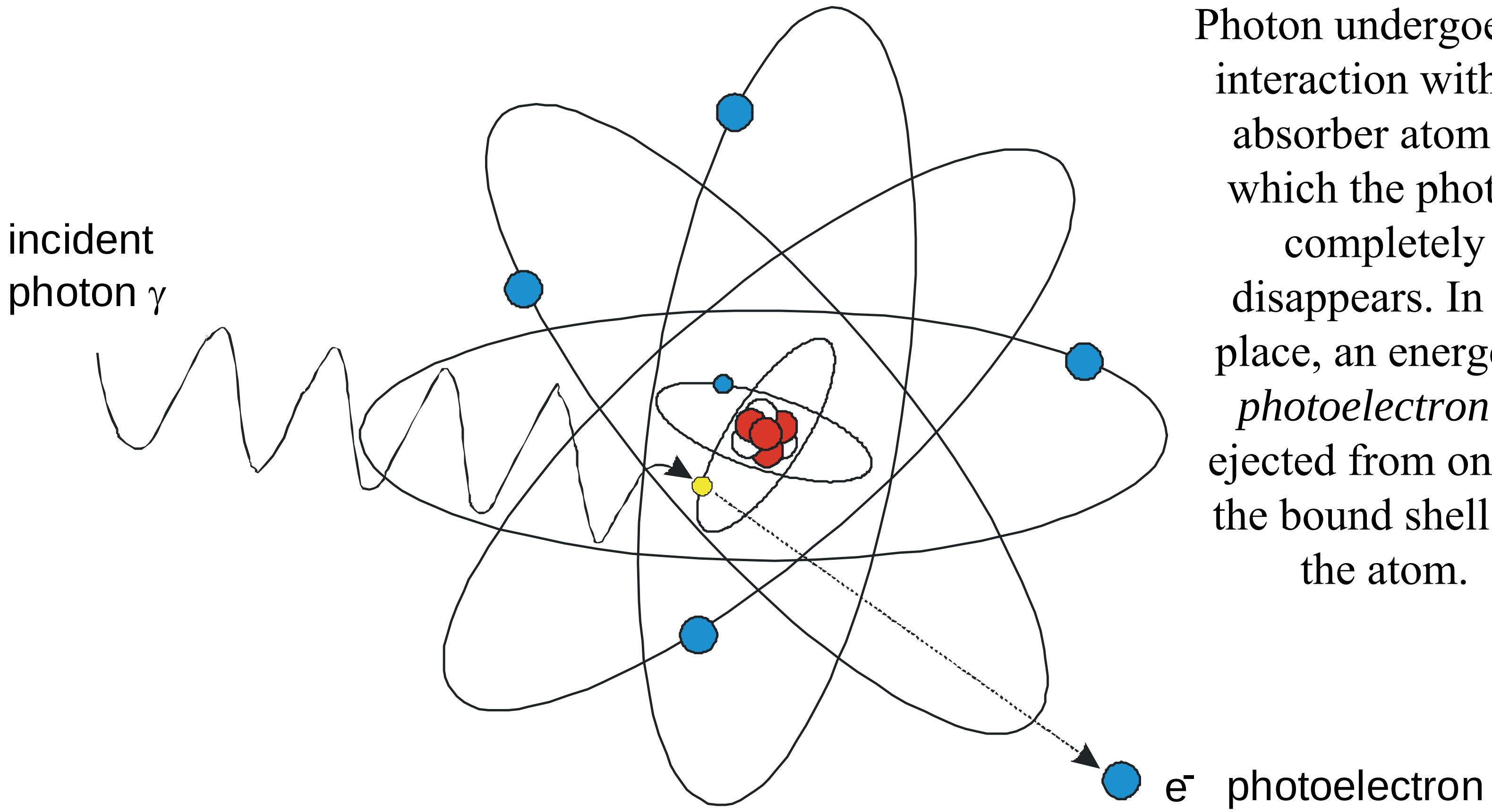
Photons are thus electromagnetic radiation with zero mass, zero charge, and a velocity that is always c, the speed of light. Because they are electrically neutral, they do not steadily lose energy via coulombic interactions with atomic electrons as do charged particles. Instead they travel some considerable distance before undergoing a more "catastrophic" interaction. All of the photon interactions of interest to us in this course lead to partial or total transfer of the photon energy to electron energy. Thus the history of a photon in material is characterized by the sudden disappearance of the photon or by scattering through significant angles with significant energy loss.

Photon interaction with matter

- It can penetrate the section of matter without interacting
- It can interact with the matter and be completely absorbed by depositing its energy
- It can interact and be scattered or deflected from its original direction and deposit part of its energy



Gamma rays: Photoelectric effect

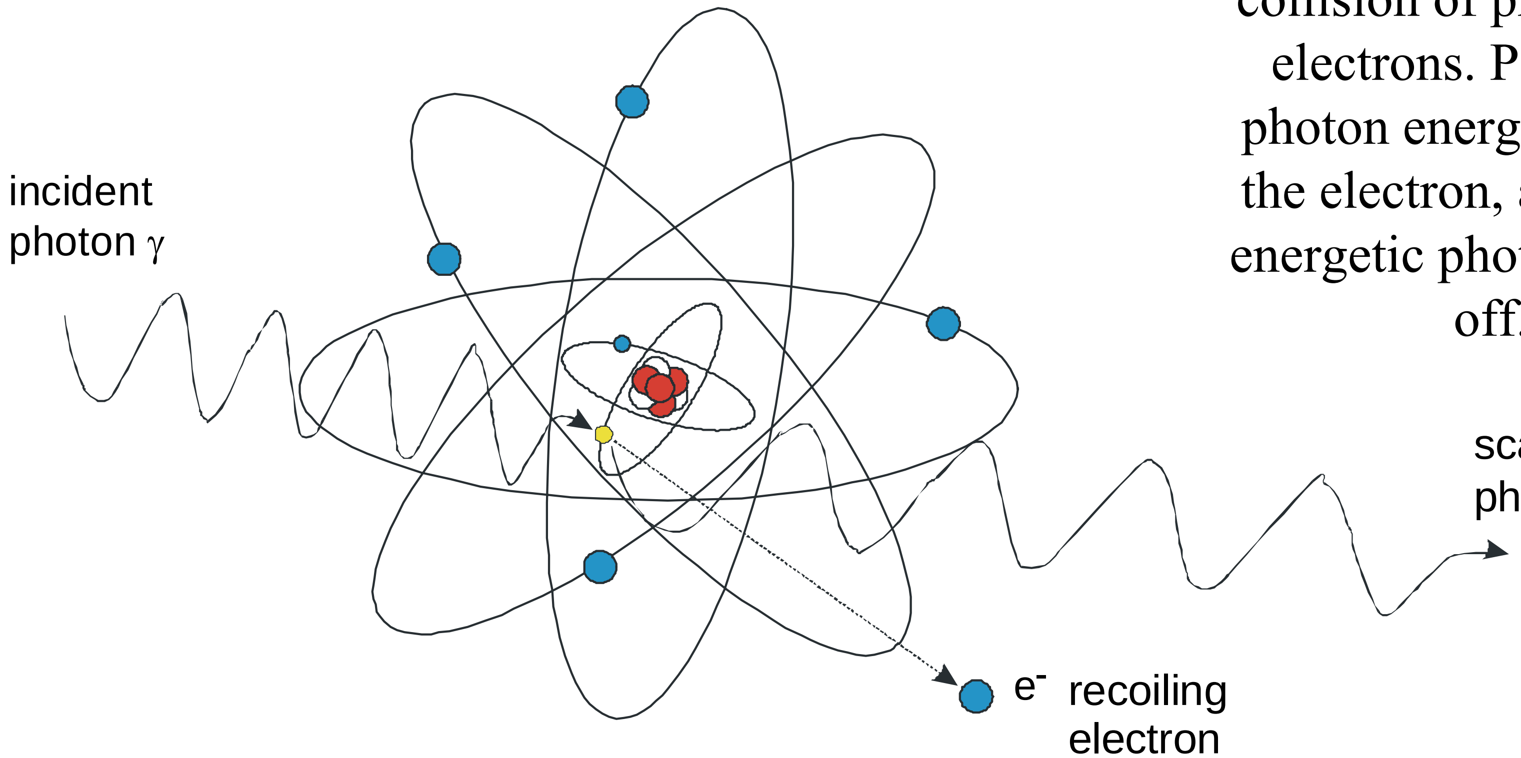


Photon undergoes an interaction with an absorber atom in which the photon completely disappears. In its place, an energetic *photoelectron* is ejected from one of the bound shells of the atom.

$$PE \propto Z^{(4-5)} / E^3$$

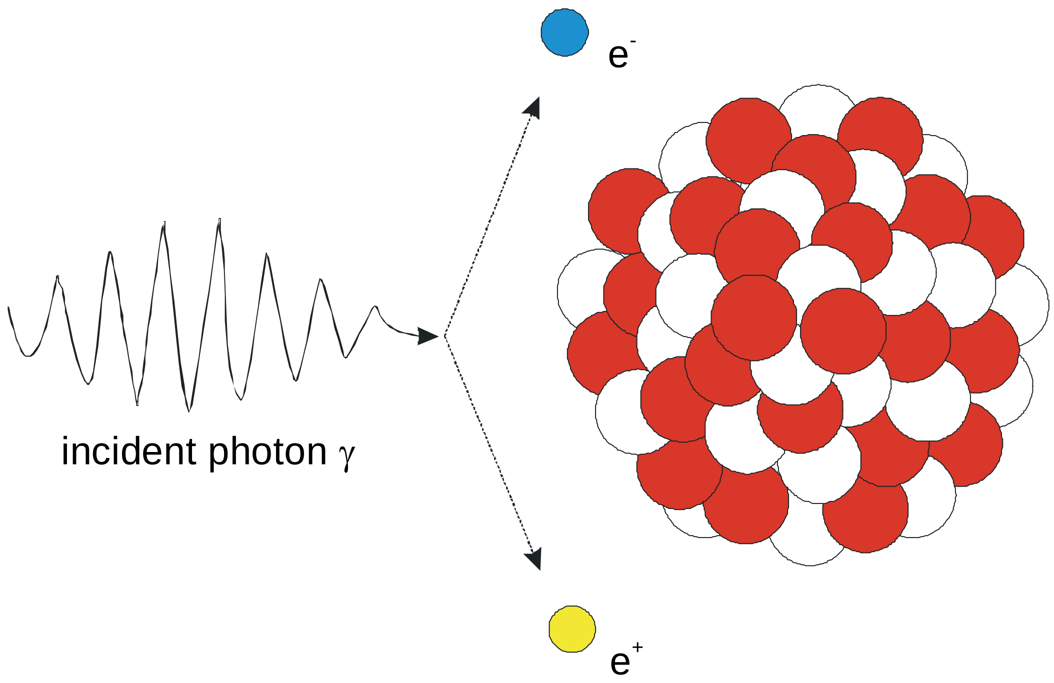
Gamma rays: Compton scattering

The **Compton effect** is equivalent to inelastic collision of photon with electrons. Part of the photon energy is lost to the electron, and a less-energetic photon bounce off.



Note: scattering – not absorption!

Gamma rays: Pair production

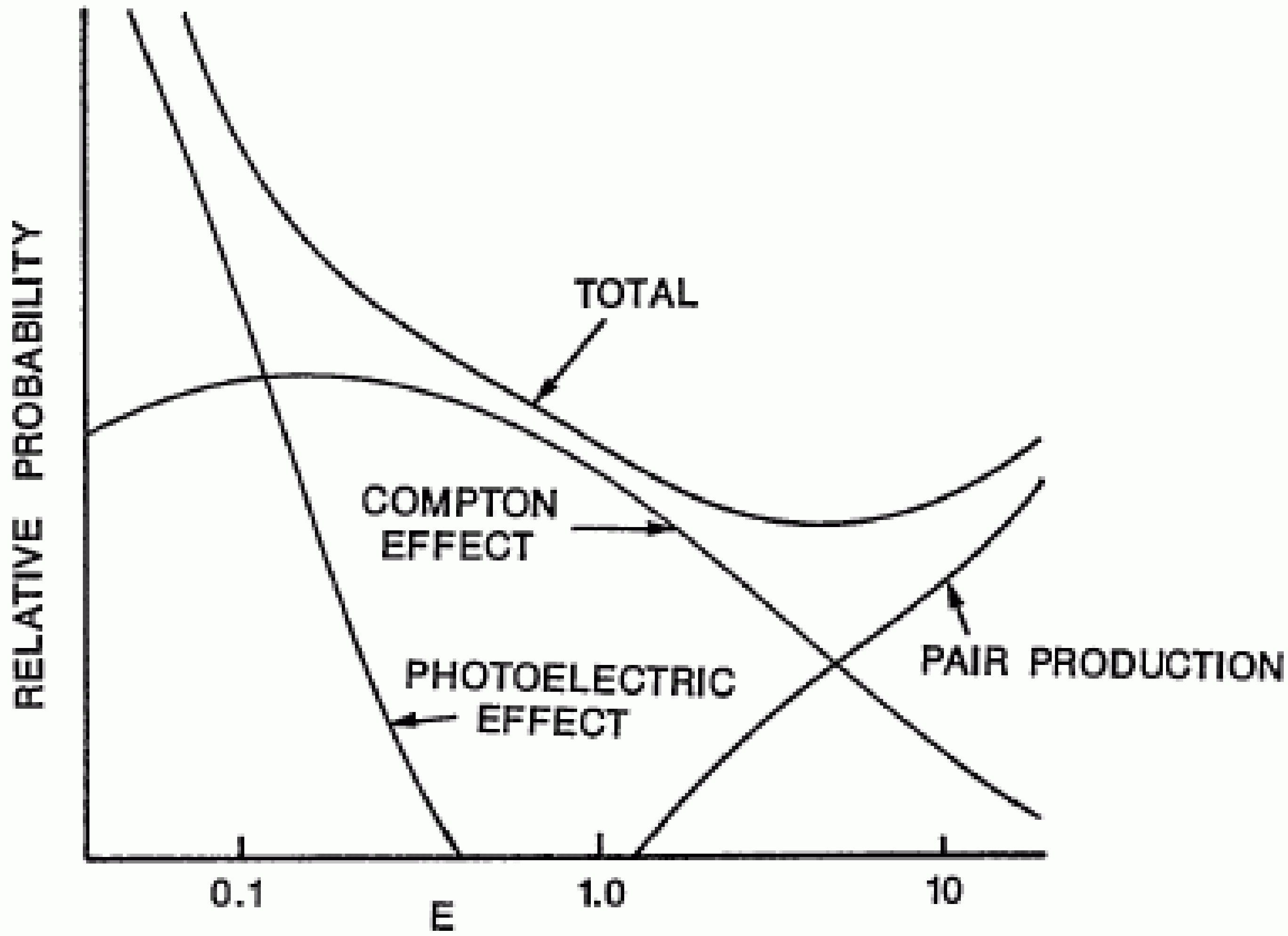


At the vicinity of an atom, a photon with energy greater than 1.02 MeV creates a positron-electron pair, and such a process is called **pair production**. Pair production also occurs in the field of an atomic electron, especially for photons with energy of more than 2.04 MeV. Pair production is not exactly the reverse of annihilation, because the former involves only one phobton, and two photons are emitted in annihilation. Note that the two electrons produced, e- and e+, are not scattered orbital electrons, but are created, *de novo*, in the energy/mass conversion of the disappearing photon.

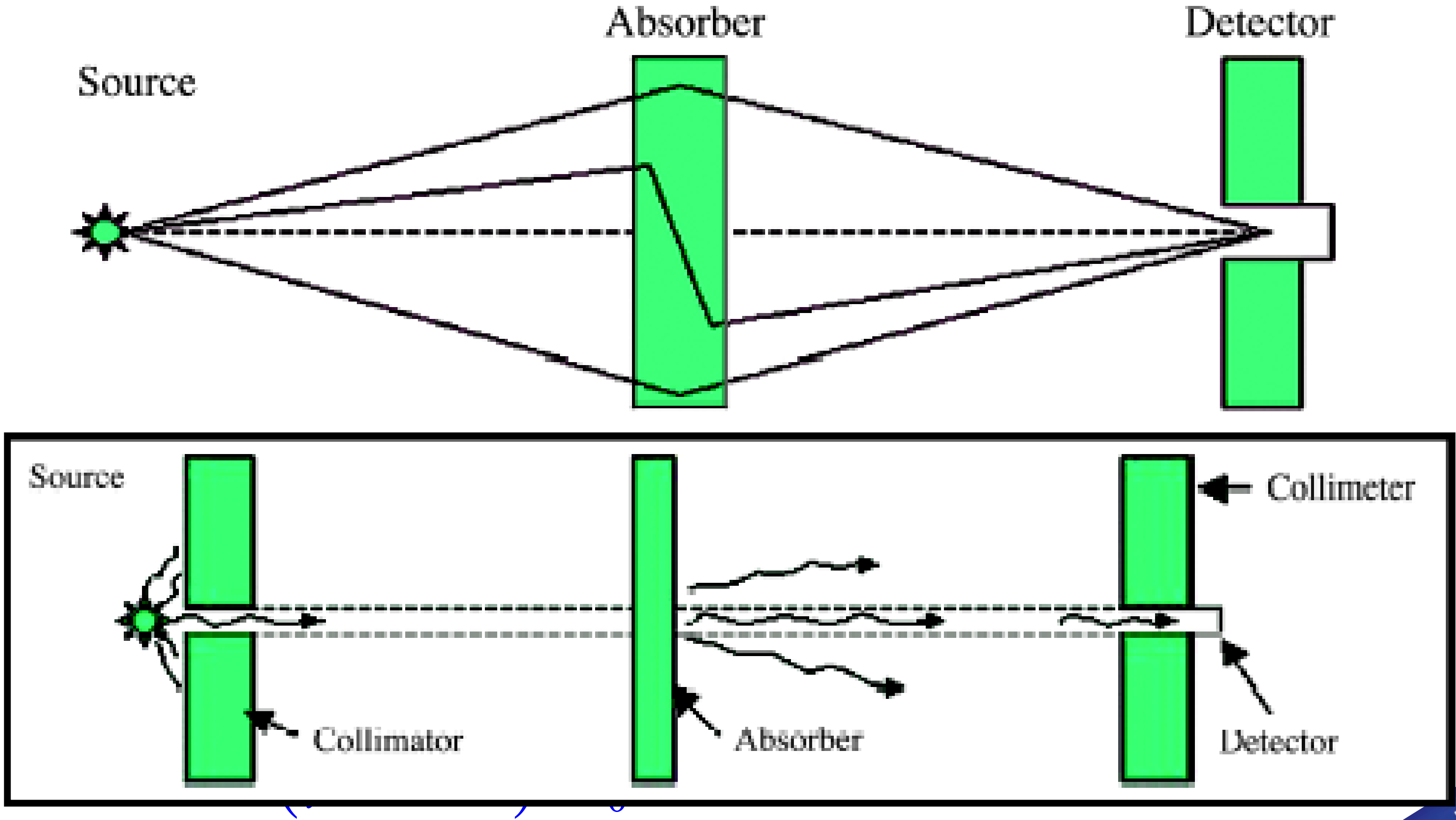
Positron annihilation:

$$e^{+} + e^{-} \rightarrow 2\ \gamma\ (511\ \text{keV})$$

Relative importance of specific interactions



Attenuation & absorption of gamma radiation



Absorption of the γ-dose

$$\mu = \mu_{pe} + \mu_{cs} + \mu_{pp}$$

Half-value thickness

$$d_{1/2} = \ln 2 / \mu$$

Medium	0.1 MeV	0.5 MeV	1 MeV	2 MeV	5 MeV
Air	35 m	62 m	76 m	120 m	200 m
Water	4 cm	7 cm	10 cm	14 cm	23 cm
Concrete	2 cm	3 cm	5 cm	7 cm	10 cm
Iron	0.2 cm	1 cm	1 cm	2 cm	3 cm
Lead	0.01 cm	0.4 cm	0.9 cm	1.3 cm	1.4 cm

Biological effects

Biological Effects of Radiation

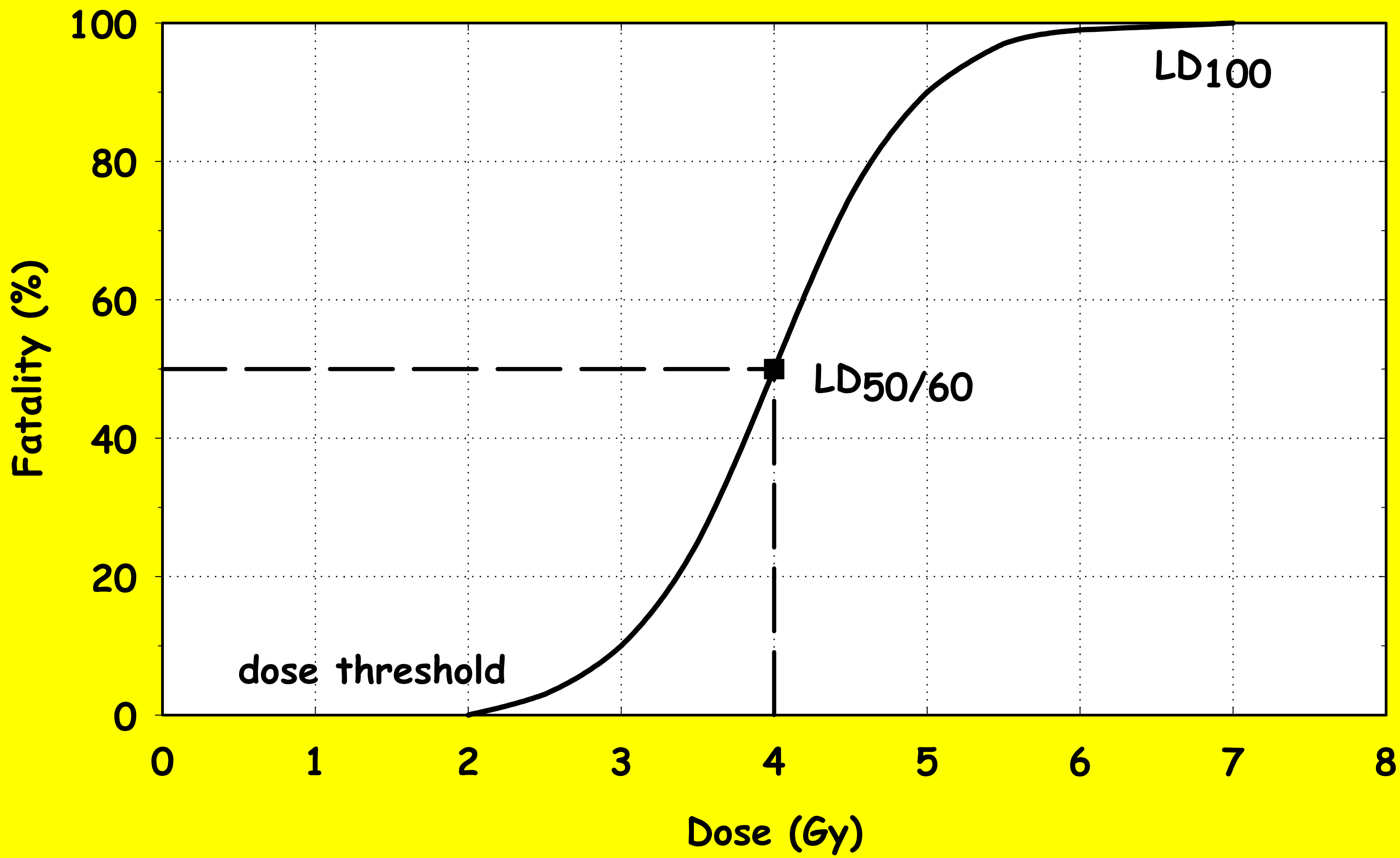
- Deterministic effects (dose threshold!)

  - acute: can be lethal!

- Stochastic effects

  - late: cancer, leukemia
  - hereditary (in offspring)

DETERMINISTIC EFFECTS OF RADIATION
ARS - Acute Radiation Syndrome



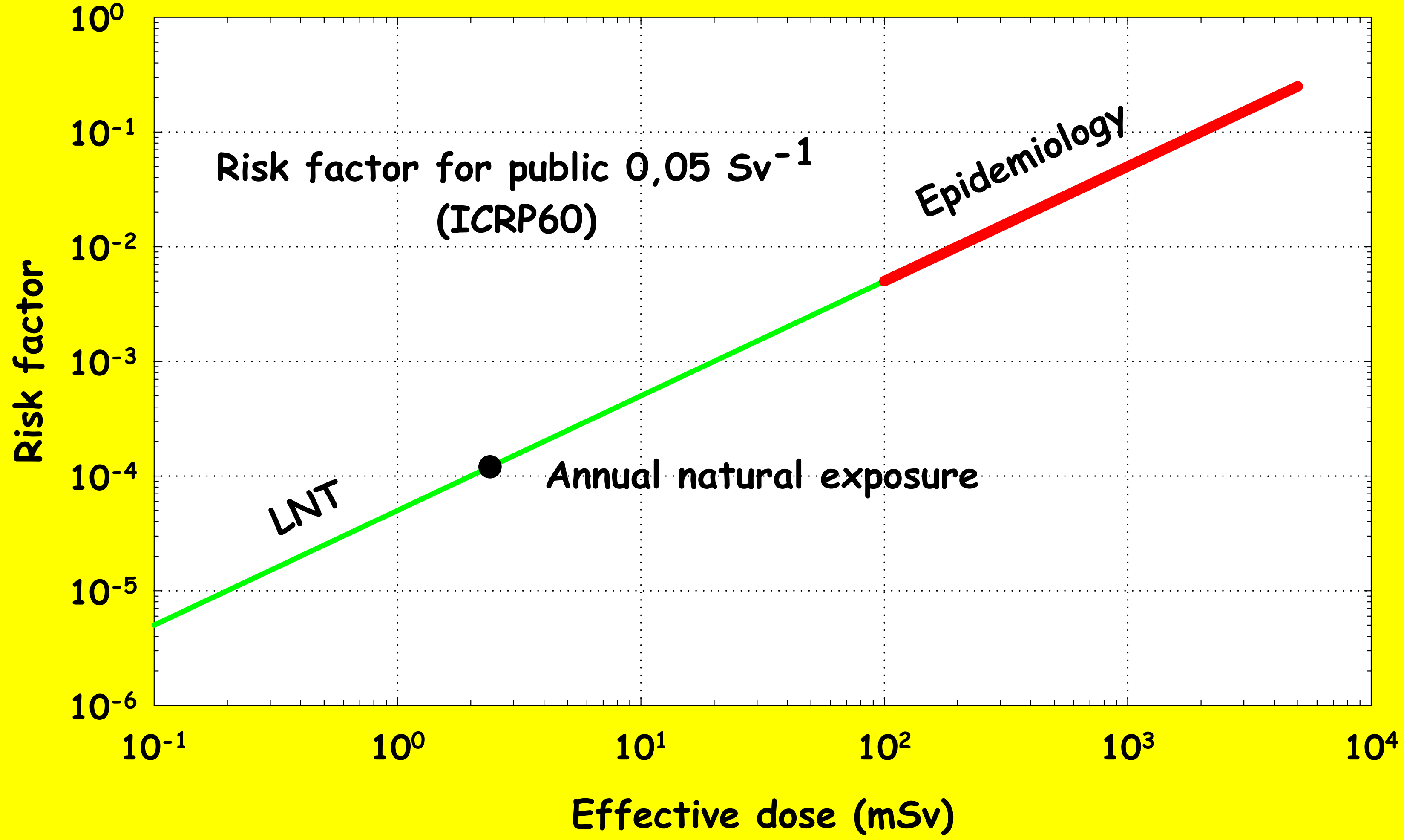
Deterministic effects

- Acute radiation syndrome ARS
  - hemopoietic s. (2 – 10 Gy)
  - gastrointestinal s. (10 – 50 Gy)
  - central nervous system s. (>50 Gy)
- skin damage
- cataract
- Sterility (temporal or permanent)

Mihran Kassabian (1870-1910)

- X-ray exposure in 1900
- death from cancer in 1910

Stochastic effects of radiation



Main features of stochastic effects

- cancer, leukemia, hereditary effects in offspring
- latent period (years, tens of years)
- probability increases with dose (LNT)

Dose and definition

Absorbed dose and dose rate

- ✓ Interaction of radiation with matter involves transfer of energy from the radiation to the matter (biological effect % to absorbed energy)
- ✓ Radiation depends on energy and intensity
- ✓ SI unit: 1 Gy =1 J kg^{-1}
- ✓ Dose rate: rate at which the absorbed dose is received (Gy s^{-1})

Weighting factor

- The biological effect depends on the type of radiation and the energy range

Type of radiation, R	Energy range	Quality or Weighting factor, w_R
Photons, electrons	All energies	1
Neutrons	< 10 keV	5
	10-100 keV	10
	100 keV – 2 MeV	20
	2-20 MeV	10
	>20 MeV	5
Protons	< 20 MeV	5
Alpha particles, fission fragments, heavy nuclei		20

* ICRP Publication 74, Annal of the ICRP 26 (3/4), 1996

Tissue/organs sensibility

Tissue / organ sensitivity

(stochastic effects)

Effective dose *E* $E = \Sigma\, w_T H_T$

Tissue weighting factors w_T

Tissue / organ	w_T
gonads	0,20
red bone marrow, colon, lung, stomach	0,12
bladder, breast, liver, oesophagus, thyroid	0,05
skin, bone surface	0,01
remainder	0,05

Equivalent and effective dose

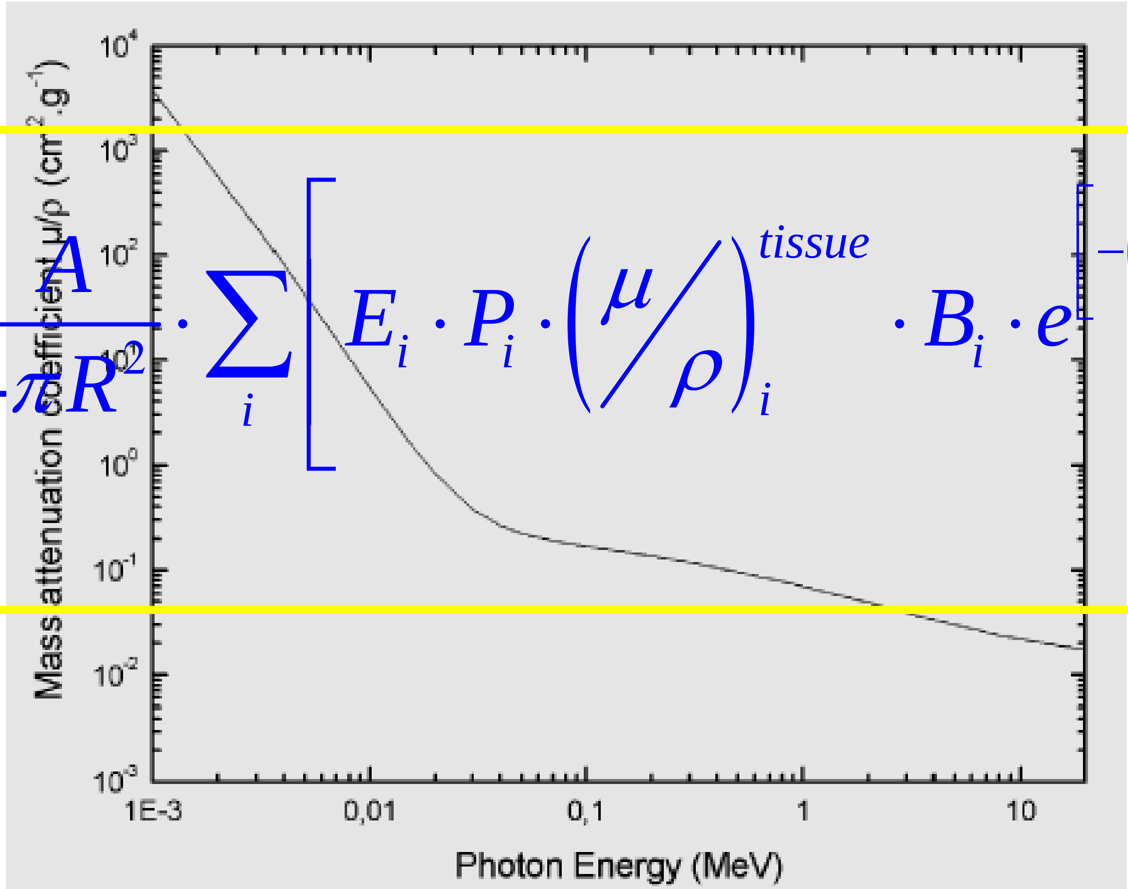
- ✓ Equivalent dose in a tissue or organ: $H_T = D_{T,R} \cdot \omega_R$
- ✓ If several types of radiation: $H_T = \sum_R \left(D_{T,R} \cdot \omega_R \right)$
- ✓ SI unit: 1 Sv = 1 J kg^{-1}
- ✓ Equivalent dose rate: $\frac{dH_T}{dt} = \frac{dD_{T,R}}{dt} \cdot \omega_R$ (Sv/s or mSv/h)
- ✓ Effective dose (E) : introduce tissue weighting factor (e.g. Gonads =0.20, Skin = 0.01), hence

$$E = \sum_T \left(H_T \cdot \omega_T \right)$$

The radiation doses in short words

- Absorbed dose: amount of radiation aborbed per unit mass of material (Gy = J.kg^{-1})
- Dose rate: absorbed dose per unit time (Gy.s^{-1})
- Equivalent dose: dose rate weighted for the biological effects of different types of radiation (Sv.h^{-1})
- Effective rate: equivalent dose weighted to take into account the damage sensitivities to different tissues (Sv.h^{-1})

Absorption in tissue and calculation of the equivalent dose rate



$$\frac{dH}{dt} = \frac{A}{4\pi R^2} \cdot \sum_i \left[E_i \cdot P_i \cdot \left(\mu / \rho\right)_i^{tissue} \cdot B_i \cdot e^{\left[-\left(\mu / \rho\right)_i^{shield} \rho d\right]} \right]$$

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Case Study: γ-dosimetry and shielding

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Exercises: γ-dosimetry and shielding

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Exercice 1: Irradiator

Irradiators are γ-sources (e.g. ^{137}Cs, ^{60}Co) used for food irradiation, radiation induced mutation, sterilization, medicine purposes, etc…

Exercise: A ^{60}Co gamma ray irradiation containing a 2TBq source is directed at a 30 cm thick concrete wall. The wall is situated at 7.5 m from the source. What the exposure rate behind the wall?

Co60
5.27 y
10.47 m

Dosimetry and Shielding

27 Cobalt

Actual Chart: Karlsruhe

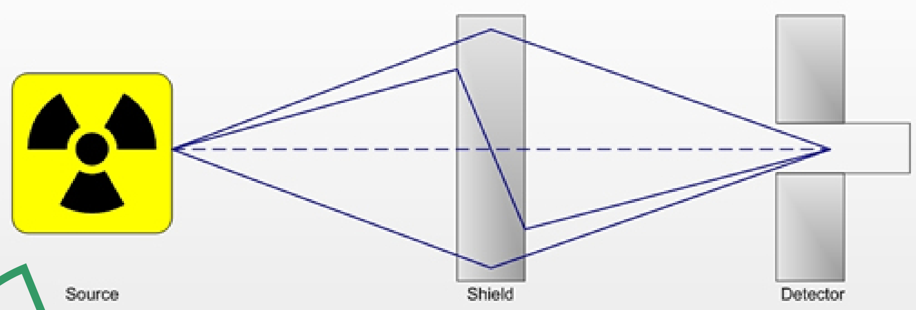
Element: Co
Mass: 60
Nuclide Mixtures Selector

Dosimetry and Shielding | Options

Source strength
Activity(Bq): 2e12

Shielding material
Concrete: 30 cm

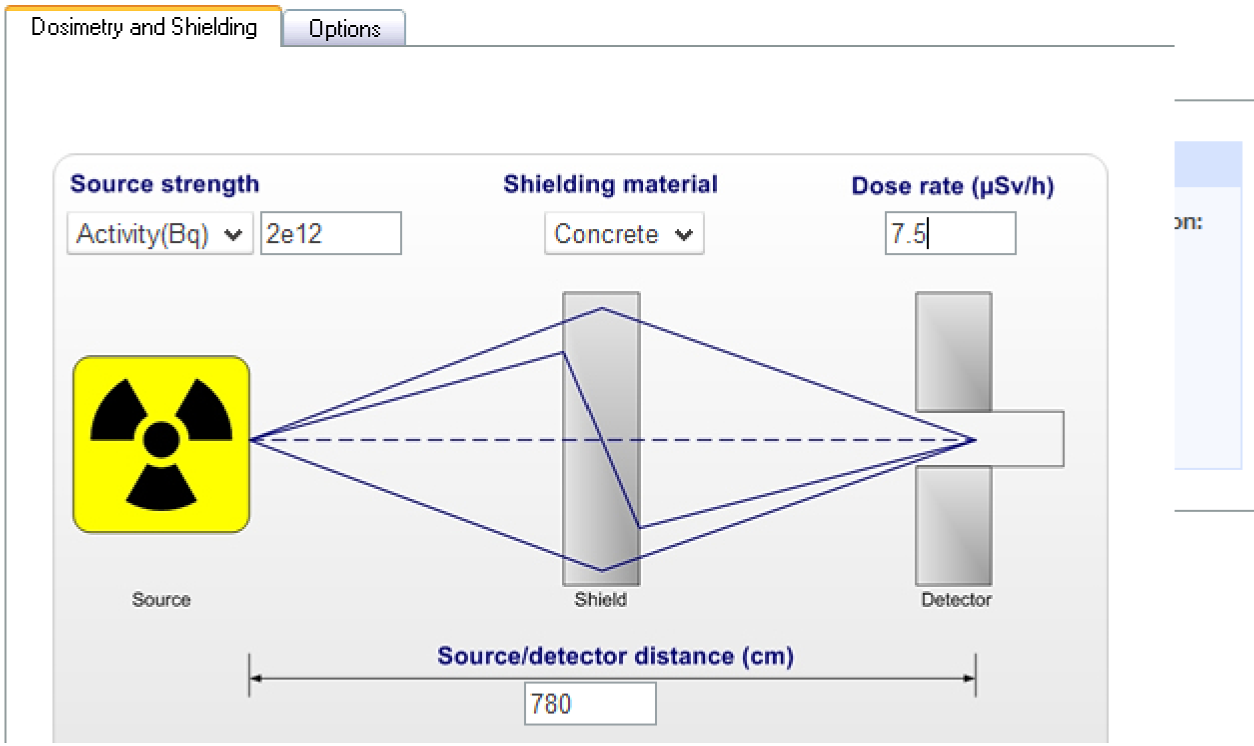
Dose rate (μSv/h)



Half-Value Shield Thickness(cm)	1.03E+01
Tenth-Value Shield Thickness(cm)	3.09E+01
Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h)	3.27E-01
Gamma Dose Rate (μSv/h)	1.26E+03

Exercise 1 (2)

- Regulation impose an exposure rate outside the room of 7.5 μSv/h max. What thickness of wall would we then need?
- We want to restrict the exposure rate inside the room (@1m from the irradiator) to 10 μSv/h using lead. Calculate the required thickness.



Half-Value Shield Thickness(cm)	1.03E+01
Tenth-Value Shield Thickness(cm)	3.09E+01
Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h)	3.37E-01
Shielding Thickness| required(cm)	8.01E+01
Resulting Gamma| Dose Rate(µSv/h)	7.50E+00

Exercise 2: ^{99m}Tc in medicine

^{99m}Tc is used in radioactive isotope medical tests, for example as a radioactive tracer that medical equipment can detect in the body. It is well suited to the role because it emits readily detectable 140 keV gamma rays, and it has a short half-life of 6.01 hours (meaning it has almost completely decayed to ^{99}Tc in 24 hours). A patient is injected 30 mCi of ^{99m}Tc. He is considered as an unshielded source during the time there is radioactivity in his body. Thus the staff is exposed to radiation. What is the equivalent dose rate that a staff member can be exposed to? (medium is tissue, 1 cm thick @1 m distance)

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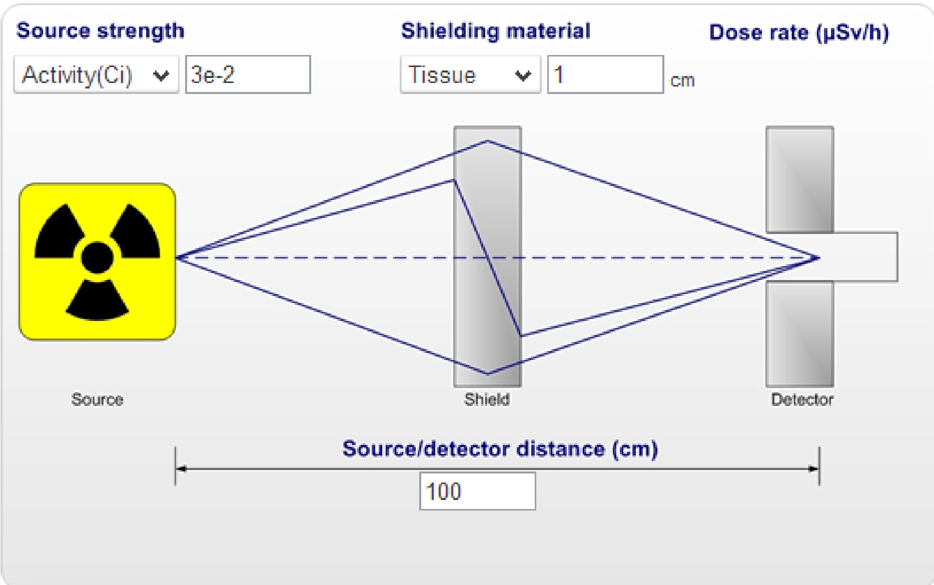
Element: Tc   Mass: 99 m   Nuclide Mixtures Selector

Dosimetry and Shielding | Options



Start   Reset

Half-Value Shield Thickness(cm)	2.89E+00
Tenth-Value Shield Thickness(cm)	1.27E+01
Equivalent Dose Rate Constant Γ(mSv·m²/GBq/h)	2.00E-02
Gamma Dose Rate (µSv/h)	1.65E+01

Distance From Patient (cm)	Exposure Rate (mR/h per mCi)	Exposure for Typical Procedures (mR)†	
		Thallium (3.5 mCi)	^{99m}Tc (30 mCi)
1	698	1,629	13,960
5	28	65	558
15	3	7	60
30	0.8	1.8	16
100	0.07	0.2	1.4

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